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Thermal influences during rotary draw bending of tubes from stainless steel

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Abstract

Rotary draw bending of tubes is a widely used forming process. Tubes made of stainless steel e.g. from AISI 304 (X5 CrNi 18 9) are used in exhaust systems, in the food industry or to guide chemicals. The formability of this austenitic stainless steel is high, because of its high work hardening.. The work hardening is caused by the temperature depending formation of martensite. The temporal temperature progressions as well as the local heat distributions have to be considered for the simulation of the bending process. The flow curves of AISI 304 were gained under nearly isothermal conditions. Other input Data were taken from literature. The results of the thermal coupled FE-Simulations compared to the results from practical experiments showed, that the temperature could not be calculated with good accordance. The reasons can be in simplifications in the FE-model.

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Keywords: Rotary draw bending; Thermally coupled simulation

1. Introduction

New products often are designed to save space. A typical example is exhaust systems in cars. Therefore tube bends with small bending radii are required. To produce these bows, the formability of the raw materials should be used completely. This is only possible, if the influences from the forming process on the formability are understood. One essential influence is the temperature changes during the forming procedure. This is true in particular, if the flow curves of the semi finished products are heavily dependent on temperature. This dependency is investigated

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by different scientists for metastable austenitic steels. Newer works are from B. Springub (2004) or C. Müller-Bollenhagen (2011).

Nomenclature

B	bending factor
R	bending Radius
d	tube diameter
W	wall thickness factor
s	wall thickness
k_f	flow stress
a, b, c	coefficients of the flow curve
φ	true strain
μ	friction coefficient

2. Introduction of Rotary draw bending

Rotary draw bending (Fig. 1) is widely used to produce bends with small bending factors B. The bending factor is the quotient of the bending radius R to the tube diameter d.

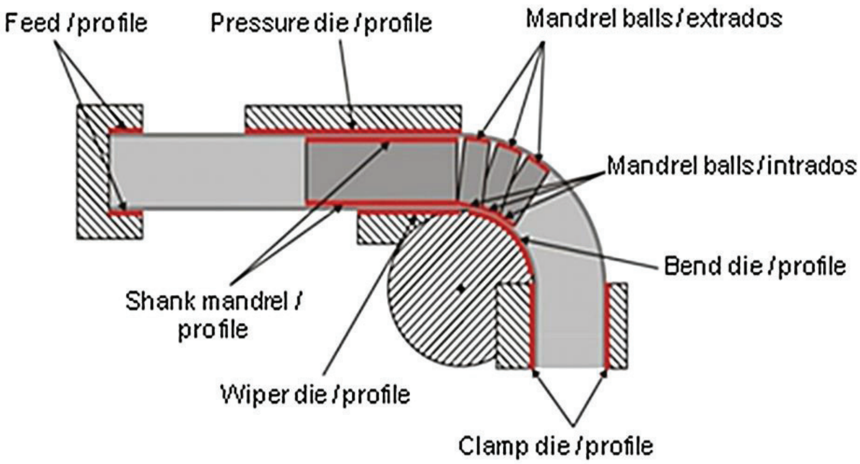

Fig. 1. Basic arrangement of the toolset for rotary draw bending.

The forming process is described as following. The tube is inserted into the feed and fixed between the clamp dies. The pressure die positioned with contact to the tube. Next step is the real bending process. The bending die is rotating around its center and the tube is wrapped around the bending die. The mandrel is necessary to prevent the extrados from falling in. For big wall thickness factors W (quotient of tube diameter d and wall thickness s) the wiper die is used to prevent wrinkling in the intrados.

3. Uniaxial tensile tests

3.1. Heat flow in uniaxial tensile tests

During uniaxial tensile tests mechanical work is brought into the specimens. This work is the integral of the product of drawing force and the specimens elongation. It is dissipated to a great amount into heat within the specimens. Consequentially, the temperature of the specimens rises. Assuming a uniform elongation concerning the parallel length, this area is heated up even. Due to the larger cross sectional area in the Zone between parallel length and the chuck heads, elongation is decreased and heat capacity is increased in this area. This results in lower temperatures in and heat flow from the parallel length to this area. Thus temperature is non-uniform in the initial measuring length. Furthermore, heat is emitted to the ambient air by convection. Figure 2 shows the heat flows in the specimen schematically. The convectional heat flow is biggest in the area with the highest temperature. So convection tends to equalize the temperature profile. This leads to lower peak values of temperature and a more uniform temperature distribution within the initial measuring length as well.

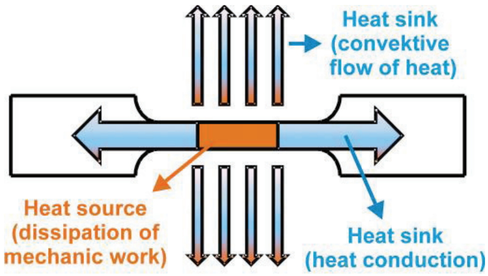

Fig. 2. Heat flow in specimens for uniaxial tensile tests.

Dissipation of forming energy as well as heat conduction to the clamping areas are proportional to the cross sectional area. Convective heat transfer to the surrounding just acts on the specimen surface, resulting in a lower surface temperature. So, a temperature profile is also built up concerning the cross section of the specimen. Hence, the influence of convection falls and both peak temperature and thermal inhomogeneities in the initial measuring length rise with increasing thicknesses of the specimens.

The local temperature distribution concerning the measuring length usually shows a maximum near the middle of the specimen. This is also the area, where necking will occur in most cases. The local rise of temperature leads subsequently to the local weakening of the specimen. This failure mechanism is found also in real forming processes e.g. the rotational draw bending.

3.2. Flow curves under nearly isothermal condition

Isothermal uniaxial tensile tests are needed to calculate isothermal flow curves. Flow curves of metals are generally temperature dependent. To quantify the temperature dependency, uniaxial tensile tests were carried out under almost isothermal conditions in a temperate chamber. The experimental setup is shown in Fig. 3a, the gained curves of true stresses vs. true strains in Fig.3b. The chamber is heated with hot air from a heat gun to achieve a high convection. Temperature sensors fixed on the surface of the specimens measured maximum temperature differences of 4°C.

The influence of different temperatures becomes evident from true strains φ of ca. 0,1 on. From then, the slopes of the curves depend on temperatures. The flow stresses are higher at lower temperatures. The temperature range for the experiments was chosen so that the maximum temperature is higher than the temperature of the specimens under adiabatic conditions. The curves were linearised for use in FE-Simulations. The flow curve used is given by equation 1, the parameters are listed in Tab. 1. A more detailed description is given by R. Steinheimer and B. Engel (2011).

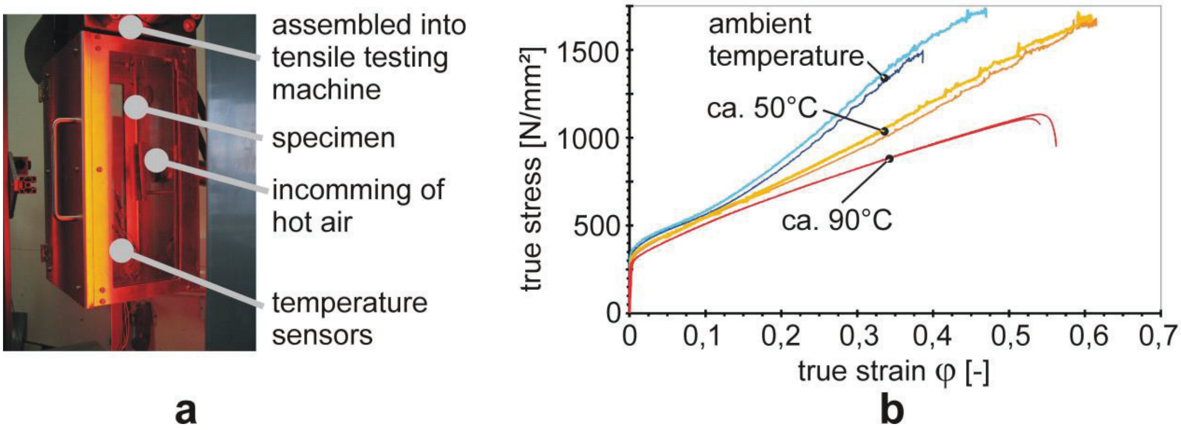

Fig. 3. Temperature chamber (a), True stress vs. true strain curves under different temperatures (b).

$$k_f = a + b\varphi^{C}. \tag{1}$$

Table 1. Coefficients for the flow curves used in FE-Simulation.

Temperature T (°C)	Coefficient a (N/mm^2)	Coefficient b (N/mm²)	Coefficent c (-)
20	350	2900	1
50	325	2250	1
90	290	1620	1

4. Rotary draw bending

4.1. Practical experiments

Practical bends were carried out with different bending velocities. The tubes were made by roll forming with longitudinal welding, calibration and additional heat treatment. The material was AISI 304 (X 5 CrNi 18 9). The outer tube diameter is 40 mm, the wall thickness is 2 mm.

The intrados of the tube is in contact with the rotating hub and the mandrel, the contact of the extrados in the bending zone is just local to the bending mandrel. Therefore the flow of dissipated forming energy from the intrados to the hub and to the mandrel is greater than from the extrados to the mandrel. There is an additional heat transfer by convection from the extrados to the ambient air.

A rotating hub was equipped with optical temperature sensors to measure the temperatures at the intrados. The experimental setup and results for the angular velocities of 15 and 1.5 °/s are shown in Figure 4. Because of the arrangement of the sensors, sensor 1 measures already shortly after the start and sensor 2 is located at a bending angle of 45 ° and therefore measures from about 50 ° on. Sensor 3 can detect the optical tube short before 90 °.The temperatures rise from the ambient temperature towards the end of the bending procedure at 90 °. This rise in temperature is caused by the dissipation of forming energy and frictional heat. The heat flow to the tools and to the ambient air is time dependent. The separation of these effects seems not to be possible with practical experiments. This only can be achieved with finite element simulations.

The temperature change on the outer sheets can be measured from a bending angle of approximately 30 ° with a thermal camera. In the bending speed of 15 °/s maximum temperatures of 75 °C were measured. The temperature of the extrados is therefore significantly higher than in the region of the intrados. A major reason for this effect is certainly the heat transfer to the rotating hub.

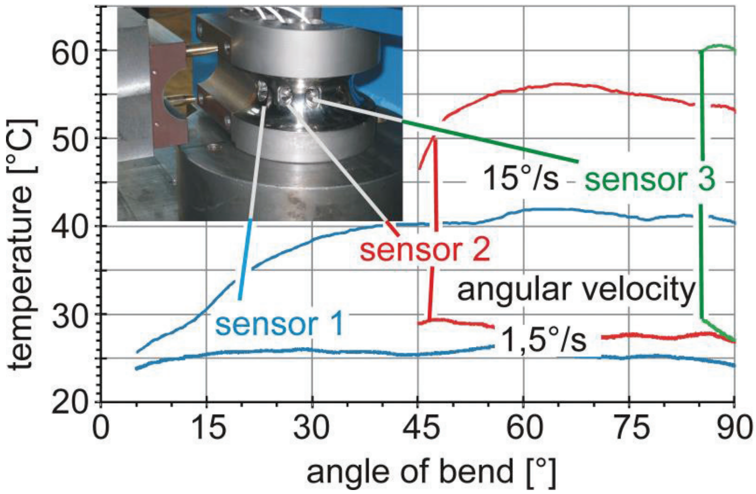

Fig. 4. Rotating hub with optical temperature sensors, Temperature evolution during bending.

4.2. Finite element simulations

The strains in rotary draw bending usually are mostly determined by the change of geometry from semi-finished to the finished product. The temperature profiles are influenced by far more effects. These are heat generation by friction (see P. Groche and N. Möller) and dissipation of forming energy and heat transfer by convection to the surrounding air as well as heat flow to tools. Furthermore, local transients occur due to heat conduction in the component itself. Heat fluxes are time-consuming and therefore depending on forming speed. The coefficients themselves are dependent on both relative velocities and surface temperatures. Overall, it seems not possible to fit in all interdependencies in FE simulations. The program used was Abaqus of Dassault Systems, France

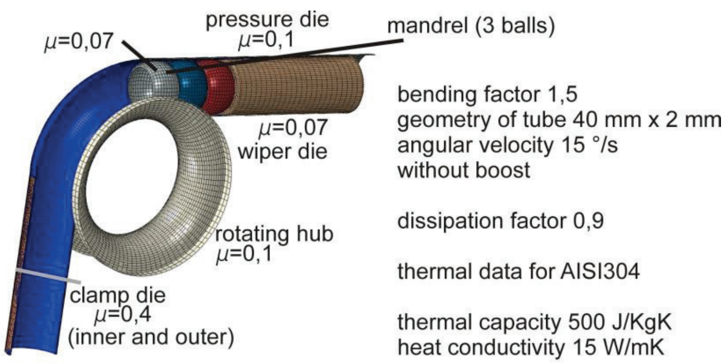

Fig. 5. Model for thermally coupled FE-simulations of rotary draw bending processes.

Friction coefficients and thermal material properties were therefore treated as constants. The flow curves at different temperatures were gained from nearly isothermal tensile tests described earlier. The FE-model for a bending factor of 1.5 is shown in Figure 5. The dissipation factor represents the fraction of forming energy, which is converted to heat (taken from R. Kopp and H. Wiegels, 1998). The heat transfer to the tools is modeled depending on contact conditions. For distances between the tube and the tool greater than 0.1 mm, there is no heat flow. For smaller distances, the same temperatures on the surfaces of tools and the tube are assumed. Convection to ambient air was neglected.

The strains and the temperature change were analyzed. This is illustrated in Figure 6.

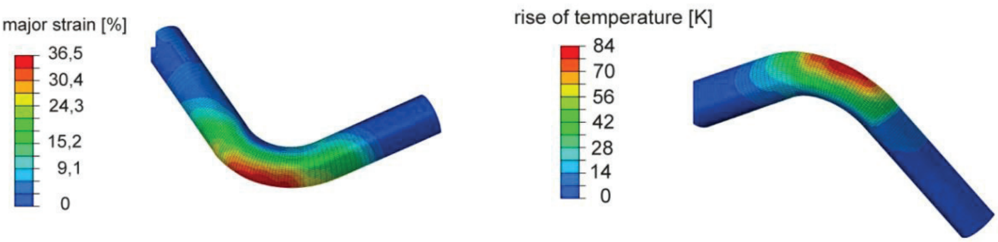

Fig. 6. Strain and rise of temperature gained by FE-simulation

The maximum of the major strain in the extrados is about 10% higher than in the practical experiment. The temperature changes, however, differ much more. In practical experiments, maximum temperatures of 75 °C were measured in the region of the extrados. The temperature in FE-simulation rises to a maximum of around 109 °C. This may be due to the fact that the convective heat transfer was not considered. The temperatures in the regions of contact to the tools are to low especially in the area of contact to the rotating hub and the clamping area. The contact conditions used may be responsible for the calculation of these excessive heat flows.

5. Conclusions

Thermally coupled FE simulations of tool-based metal forming processes require a great variety of input data. These can be determined by experiments. However, the measured correlations and interactions cannot always be fitted into existing commercial FE-simulation software and the model must therefore simplified further. For example, the dependency of heat transfer between the component and tools from the contact normal pressure has been modeled by a contact condition. Despite the quantitative imperfections of the results, the qualitative relationships are calculated correctly.

Current work concentrates on a more precise experimental determination of flow curves. The new experimental setup uses tempered water instead of air. The flow velocity is higher also. This leads to a more homogeneous temperature according the initial measuring length of specimens in uniaxial tensile tests. First results are, that even this rather small improvements lead to clearly measurable advances in the uniform elongation.

Another research field is to influence the temperature distribution with active local cooling and heating respectively. The aim is to get bends with bigger bending factors or wall thickness factors.

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